A Level Physics CIE

YOUR NOTES

9. Electricity

CONTENTS

9.1 Current & Potential Difference
9.1.1 Electric Current
9.1.2 Electric Current: Calculations
9.1.3 Potential Difference
9.1.4 Electrical Power
9.2 Resistance
9.2.1 Resistance
9.2.2 Ohm's Law
9.2.3 I-V Characteristics
9.2.4 Resistance in a Filament Lamp
9.3 Resistivity
9.3.1 Resistivity
9.3.2 Resistance in Sensory Resistors

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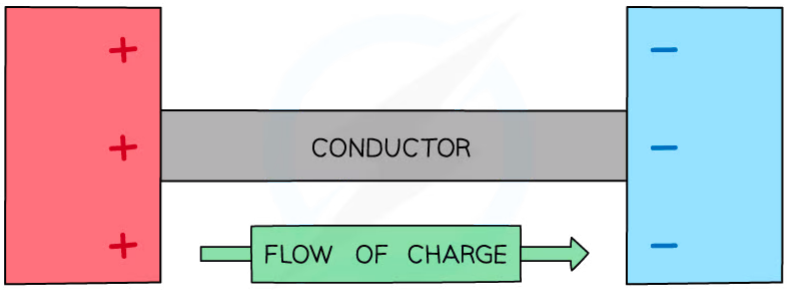
YOUR NOTES

9.1 Current & Potential Difference

9.1.1 Electric Current

Defining Electric Current

- Electric current is **the flow of charge** carriers and is measured in units of **amperes (*A*)** or **amps**
- Charge can be either positive or negative
- When two oppositely charged conductors are connected together (by a length of wire), charge will flow between the two conductors, causing a current



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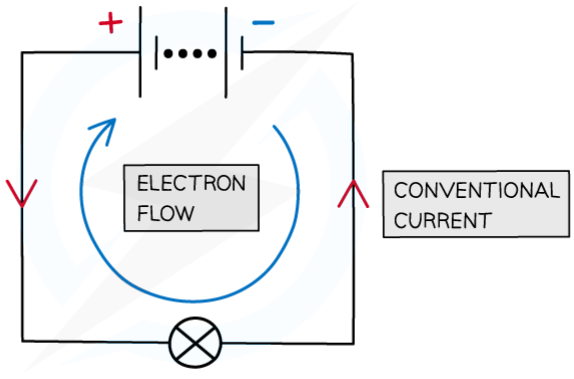
Charge can flow between two conductors. The direction of conventional current in a metal is from positive to negative

- In electrical wires, the current is a flow of **electrons**
- Electrons are negatively charged; they flow away from the negative terminal of a cell towards the positive terminal
- Conventional current is defined as the flow of positive charge from the **positive terminal of a cell to the negative terminal**
  - This is the opposite to the direction of electron flow, as conventional current was described before electric current was really understood



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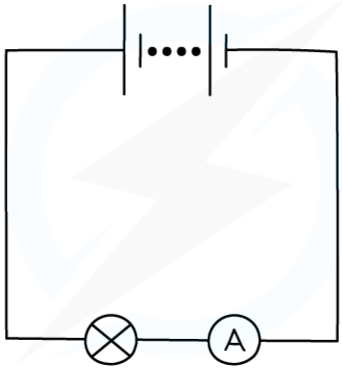
By definition, conventional current always goes from positive to negative (even through electrons go the other way)

- There are several examples of electric currents, including in household wiring and electrical appliances
- Current is measured using an **ammeter**
- Ammeters should always be connected in **series** with the part of the circuit you wish to measure the current through



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An ammeter can be used to measure the current around a circuit and always connected in series

Quantisation of Charge

- The charge on charge carriers is **quantised**
- Charge comes in definite bits – e.g. a single **proton** has a single **positive charge**, whereas a single **electron** has a single **negative charge**
- In this way, the quantity of charge can be quantised dependent on how many protons or electrons are present – positive and negative charge has a definite **minimum magnitude** and always comes in multiples of that magnitude
- This means that if we say something has a given charge, the charge is always a multiple of the charge of an electron by convention
  - The charge of an electron is -1.60×10^{-19} C
  - The charge of a proton by comparison is 1.60×10^{-19} C (this is known as the elementary charge, denoted by *e* and measured in Coulombs (C))

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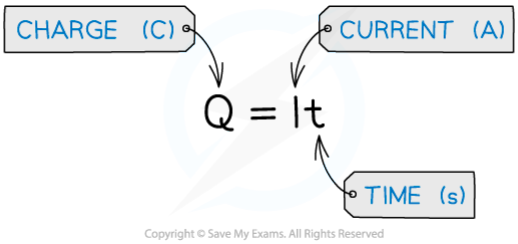
Calculating Electric Charge

- Current can also be defined as the charge passing through a circuit per unit time
- Electric charge is measured in units of **coulombs (*C*)**
- Charge, current and time are related by the following equation



Charge equation

Worked Example

When will 8 mA of current pass through an electrical circuit?

A. When 1 J of energy is used by 1 C of charge

B. When a charge of 4 C passes in 500 s

C. When a charge of 8 C passes in 100 s

D. When a charge of 1 C passes in 8 s

Answer: **B**

Step 1: Write out the equation relating current, charge and time

$$Q = It$$

Step 2: Rule out any obviously incorrect options

- Option **A** does not contain charge or time, so can be ruled out

Step 3: Try the rest of the options to determine the correct answer

- Consider option **B**:

$$I = 4 / 500 = 8 \times 10^{-3} = 8 \text{ mA}$$

- Consider option **C**:

$$I = 8 / 100 = 80 \times 10^{-3} = 80 \text{ mA}$$

- Consider option **D**:

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$I = 1 / 8 = 125 \times 10^{-3} = 125$ mA

- Therefore, the correct answer is **B**

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Exam Tip

Although electric charge can be positive or negative, since the conventional direction of current is the flow of **positive** charge the current should always be a positive value for your exam answers.

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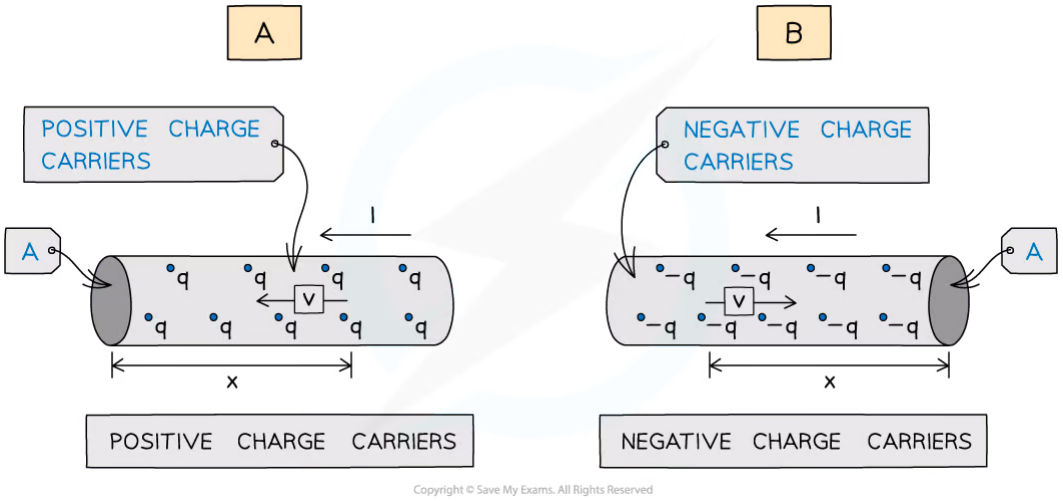
Calculating Current in a Current Carrying Conductor

YOUR NOTES

- In a conductor, current is due to the movement of charge carriers
- These charge carriers can be negative or positive, however the current is always taken to be in the same direction
- In conductors, the charge carrier is usually free electrons
- In the image below, the current in each conductor is from right to left but the charge carriers move in opposite directions shown by the direction of the drift speed *v*
  - In diagram A (positive charge carriers), the drift speed is in the **same** direction as the current
  - In diagram B (negative charge carriers), the drift speed is in the **opposite** direction to the current



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Conduction in a current-carrying conductor

- The drift speed is the average speed the charge carriers are travelling through the conductor. You will find this value is quite slow. However, since the number density of charge carriers is so large, we still see current flow happen instantaneously
- The current can be expressed in terms of the number density (number of charge carriers per unit volume) *n*, the cross-sectional area *A*, the drift speed *v* and the charge of the charge carriers *q*

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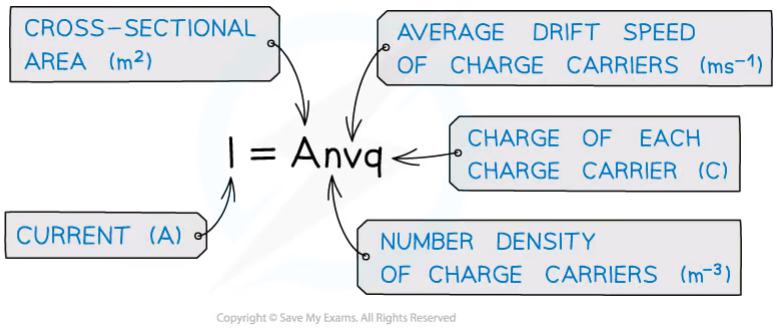
CROSS-SECTIONAL AREA (m²)
AVERAGE DRIFT SPEED OF CHARGE CARRIERS (ms⁻¹)
I = Anvq
CHARGE OF EACH CHARGE CARRIER (C)
CURRENT (A)
NUMBER DENSITY OF CHARGE CARRIERS (m⁻³)
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Current in a conductor equation

- The same equation is used whether the charge carriers are positive or negative

Worked Example

A copper wire has 9.2×10^{28} free electrons m^{-3}. The wire has a current of 3.5 A and a cross-sectional area of 1.5 mm^2.Calculate the average drift speed of the electrons.

A COPPER WIRE IS A CONDUCTOR, AND THE FREE ELECTRONS ARE CHARGE CARRIERS

STEP 1

CURRENT IN A CONDUCTOR EQUATION

$$I = Anvq$$

STEP 2

REARRANGE FOR DRIFT SPEED v

$$v = \frac{I}{Anq}$$

STEP 3

SUBSTITUTE IN VALUES

$I = 3.5\ A$

$A = 1.5 \times 10^{-6}\ m^2$ CONVERT FROM mm^2

$n = 9.2 \times 10^{28}\ m^{-3}$

$q = 1.60 \times 10^{-19}\ C$ CHARGE OF AN ELECTRON (ON DATA SHEET)

$$v = \frac{3.5}{1.5 \times 10^{-6} \times 9.2 \times 10^{28} \times 1.60 \times 10^{-19}} = 0.16 \times 10^{-3}\ ms^{-1}$$

$$= 0.16\ mms^{-1}\ (2\ s.f.)$$

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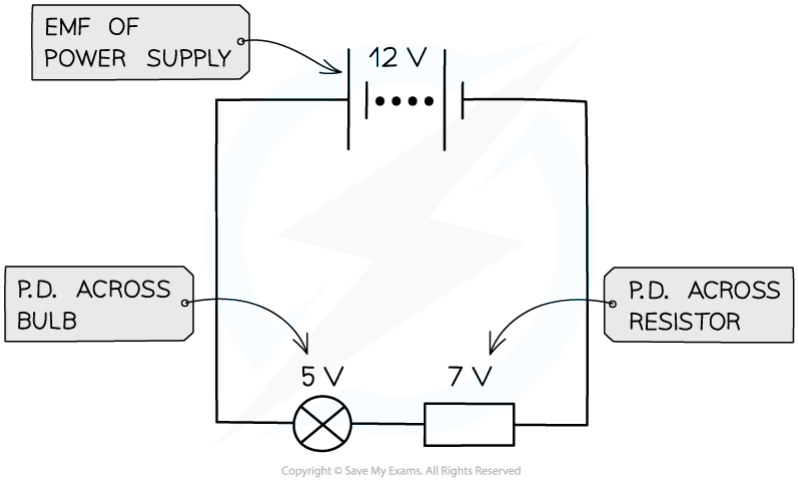
YOUR NOTES

Defining Potential Difference

- A cell makes one end of the circuit positive and the other negative. This sets up a **potential difference** (*d*) across the circuit
- The potential difference across a component in a circuit is defined as the **energy transferred per unit charge flowing from one point to another**
- The energy transfer is from electrical energy into other forms
- Potential difference is measured in **volts *(V)***. This is the same as a **Joule per coulomb (J C^{-1})**
  - If a bulb has a voltage of 3 V, every coulomb of charge passing through the bulb will lose 3 J of energy
- The potential difference of a power supply connected in series is always shared between all the components in the circuit



The potential difference is the voltage across each component in a circuit

- Potential difference or voltage is measured using a **voltmeter**
- A voltmeter is always set up in parallel to the component you are measuring the voltage for

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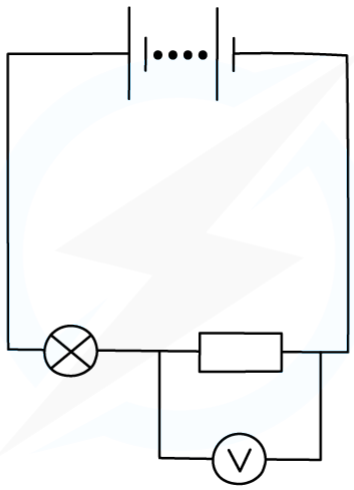

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Potential difference can be measured by connecting a voltmeter in parallel between two points in a circuit

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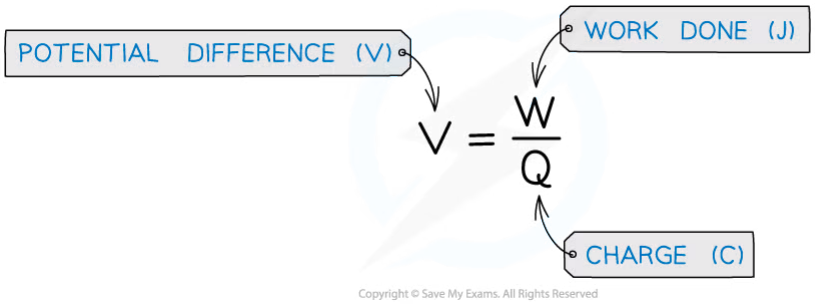
Calculating Potential Difference

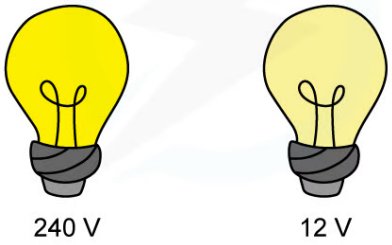
- The potential difference is defined as the **energy transferred per unit charge**
- Another measure of energy transfer is work done
- Therefore, potential difference can also be defined as the **work done per unit charge**



Potential difference is the work done per unit charge

Worked Example

A lamp is connected to a 240 V mains supply and another to a 12 V car battery.Both lamps have the same current, yet 240 V lamp glows more brightly. Explain in terms of energy transfer why the 240 V lamp is brighter than the 12 V lamp.



ANSWER:

- Both lamps have the same current, which means charge flows at the same rate in both
- The 240 V lamp has 20 times more voltage than the 12 V lamp
- Voltage is the energy transferred (work done) per unit charge
- This means the energy transferred to each coulomb of charge in the 240 V lamp is 20 times greater than for the 12 V lamp
- This makes the 240 V lamp shine much brighter than the 12 V lamp

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Exam Tip

Think of potential difference as being the **energy per coulomb** of charge transferred between two points in a circuit

YOUR NOTES

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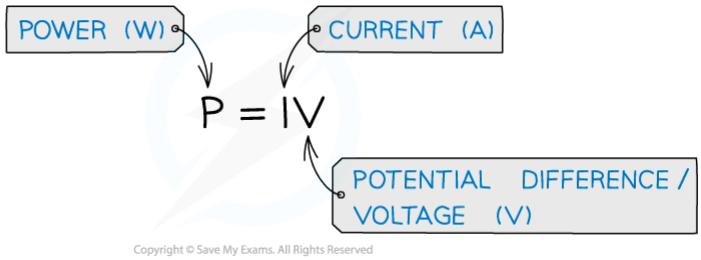
YOUR NOTES

Calculating Electrical Power

- In "Work, Energy and Power", Power *P* was defined as the **rate of doing work**
  - Potential difference is the **work done per unit charge**
  - Current is the **rate of flow of charge**
- So, the power dissipated (produced) by an electrical device is defined as:



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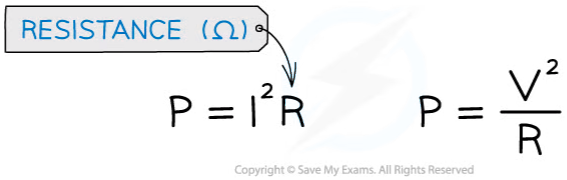
Power of a component in an electrical circuit

- Using ***V = IR*** to rearrange for either *V* or *I* and substituting into the power equation means we also write power in terms of resistance *R*



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Power equation in terms of resistance

- This means for a given resistance for example, if the current or voltage doubles the power will be four times as great

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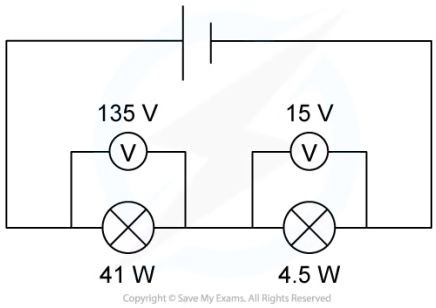
Worked Example

Two lamps are connected in series to a 150 V power supply.



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Which statement most accurately describes what happens?

A. Both lamps light normally

B. The 15 V lamp blows

C. Only the 41 W lamp lights

D. Both lamps light at less than their normal brightness

ANSWER: A

STEP 1 CALCULATE CURRENT NEEDED FOR BOTH LAMPS TO OPERATE

$P = IV$

STEP 2 REARRANGE FOR I

$I = \frac{P}{V}$

STEP 3 FOR THE 41 W LAMP: $I = \frac{41\ W}{135\ V} = 0.3\ A$

FOR THE 4.5 W LAMP: $I = \frac{4.5\ W}{15\ V} = 0.3\ A$

STEP 4 FOR BOTH TO OPERATE AT THEIR NORMAL BRIGHTNESS, A CURRENT OF 0.3 A IS REQUIRED.
SINCE THE LAMPS ARE CONNECTED IN SERIES, THE SAME CURRENT WOULD FLOW THROUGH BOTH.

STEP 5 THE LAMPS WILL LIGHT AT THEIR NORMAL BRIGHTNESS – OPTION A

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Exam Tip

You can use the mnemonic “Twinkle Twinkle Little Star, Power equals *I* squared *R*” to remember whether to multiply or divide by resistance in the power equationsWhich equation to use will depend on whether the value of current or voltage has been given in the question

YOUR NOTES

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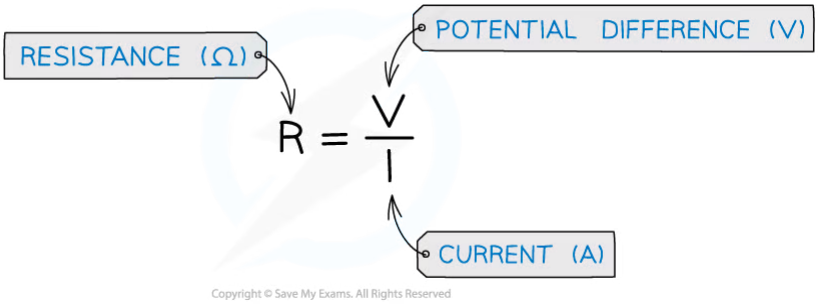
YOUR NOTES

9.2 Resistance

9.2.1 Resistance

Defining Resistance

- Resistance is defined as the **opposition** to current
  - For a given potential difference: **The higher the resistance the lower the current**
- Wires are often made from copper because copper has a low electrical resistance. This is also known as a good conductor
- The resistance *R* of a conductor is defined as the ratio of the potential difference *V* across to the current *I* in it



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Resistance of a component is the ratio of the potential difference and current

- Resistance is measured in **Ohms (Ω)**
- An Ohm is defined as one volt per ampere
- The resistance controls the size of the current in a circuit
  - A **higher** resistance means a **smaller** current
  - A **lower** resistance means a **larger** current
- All electrical components, including wires, have some value of resistance

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Calculating Resistance

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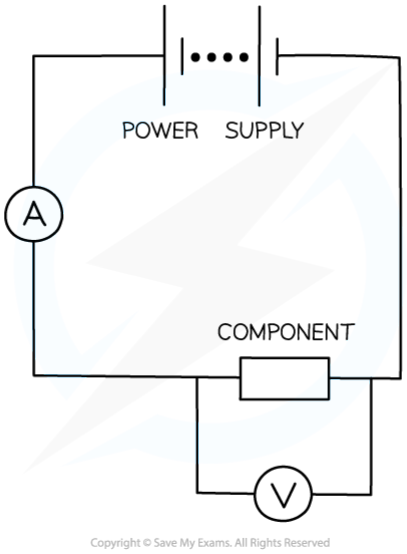
Determining Resistance

- To find the resistance of a component, we can set up a circuit like the one shown below



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A circuit to determine the resistance of a component

- The power supply should be set to a low voltage to avoid heating the component, typically 1-2 V
- Measurements of the potential difference and current should then be taken from the voltmeter and ammeter respectively
- Finally, these readings should be substituted into the resistance equation

Worked Example

A charge of 5.0 C passes through a resistor of resistance R Ω at a constant rate in 30 s.If the potential difference across the resistor is 2.0 V, calculate the value of R.

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STEP 1

RESISTANCE EQUATION

$$R = \frac{V}{I}$$

STEP 2

CALCULATE THE CURRENT FROM THE CHARGE AND TIME

$$Q = It$$

REARRANGE FOR I

$$I = \frac{Q}{t} = \frac{5.0}{30} = 0.167\,A = 0.17\,A \quad (2\ s.f.)$$

STEP 3

SUBSTITUTE VALUES INTO RESISTANCE EQUATION

$$R = \frac{2.0\,V}{0.17\,A} = 11.764... = 12.0\,\Omega \quad (2\ s.f.)$$

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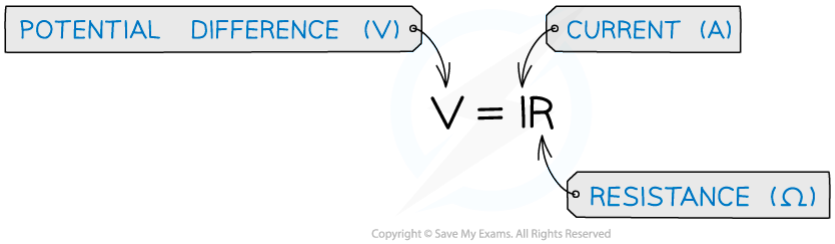
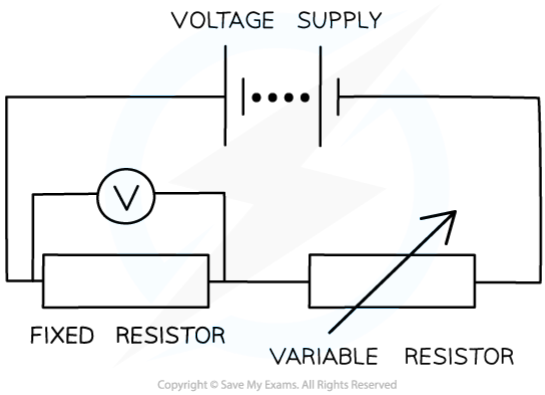
Ohm's Law

- Ohm's law states that for a conductor at a constant temperature, the **current** through it is **proportional** to the **potential difference** across it
- Constant temperature implies constant resistance
- This is shown the equation below:



Ohm's law

- The relation between potential difference across an electrical component (in this case a fixed resistor) and the current can be investigated through a circuit such as the one below



Circuit for plotting graphs of current against voltage

- By adjusting the resistance on the variable resistor, the current and potential difference will vary in the circuit. Measuring the variation of current with potential difference through the fixed resistor will produce the straight line graph below

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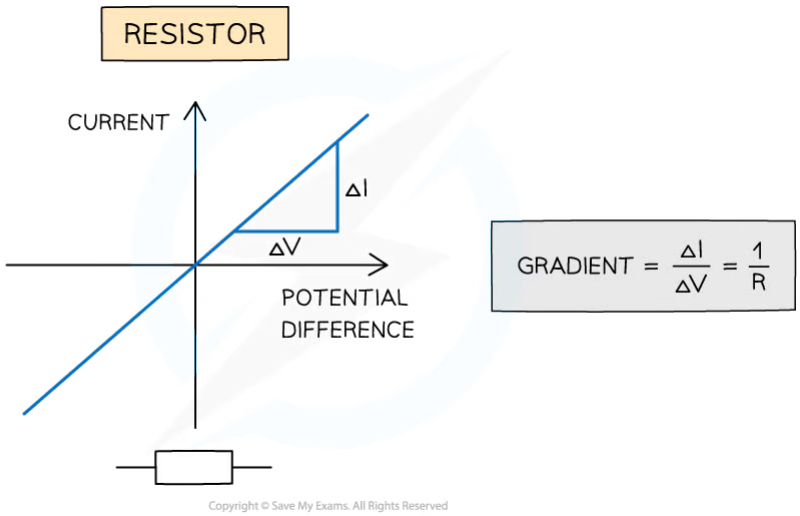

Circuit for plotting graphs of current against voltage

- Since the gradient is constant, the resistance *R* of the resistor can be calculated by using 1 ÷ gradient of the graph
- An electrical component obeys Ohm's law if its graph of current against potential difference is a **straight line** through the origin
  - A resistor obeys Ohm's law
  - A filament lamp does **not** obey Ohm's law
- This applies to any metal wires, provided that the current isn't large enough to increase their temperature

Worked Example

The current flowing through a component varies with the potential difference *V* across it as shown.

Which graph best represents how the resistance *R* varies with *V*?

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ANSWER: D

STEP 1

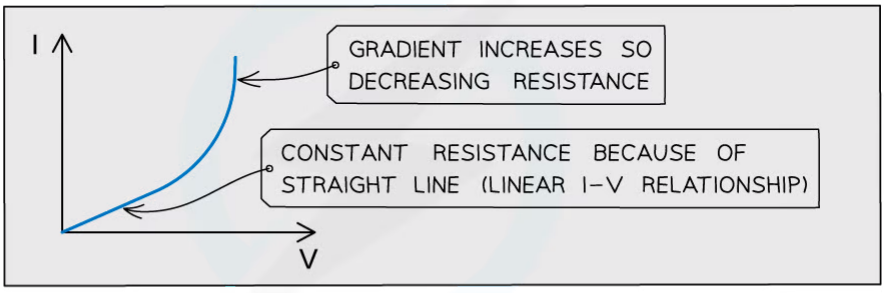
USE OHM'S LAW TO FIND R IN TERMS OF V AND I

$V = IR$ THEREFORE $R = \frac{V}{I}$

STEP 2

THIS MEANS THE GRADIENT OF THE I–V GRAPH IS EQUAL TO $\frac{1}{R}$

STEP 3


I
V
GRADIENT INCREASES SO DECREASING RESISTANCE
CONSTANT RESISTANCE BECAUSE OF STRAIGHT LINE (LINEAR I–V RELATIONSHIP)

STEP 4

HOW THIS RELATES TO R–V GRAPH

THE INITIAL LINE WILL BE HORIZONTAL SINCE RESISTANCE IS CONSTANT

THE LINE WILL THEN CURVE DOWNWARDS AS R DECREASES

OPTION D IS THE BEST DESCRIPTION OF THIS

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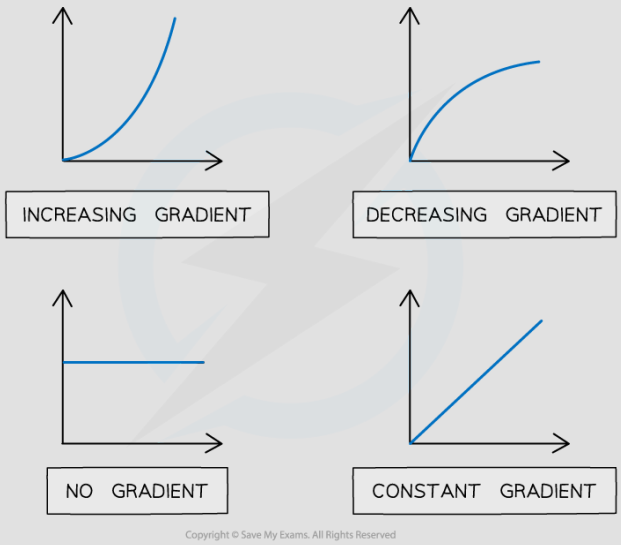
Exam Tip

- In maths, the gradient is the **slope** of the graph
- The graphs below show a summary of how the slope of the graph represents the gradient



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Graphs showing varying gradients

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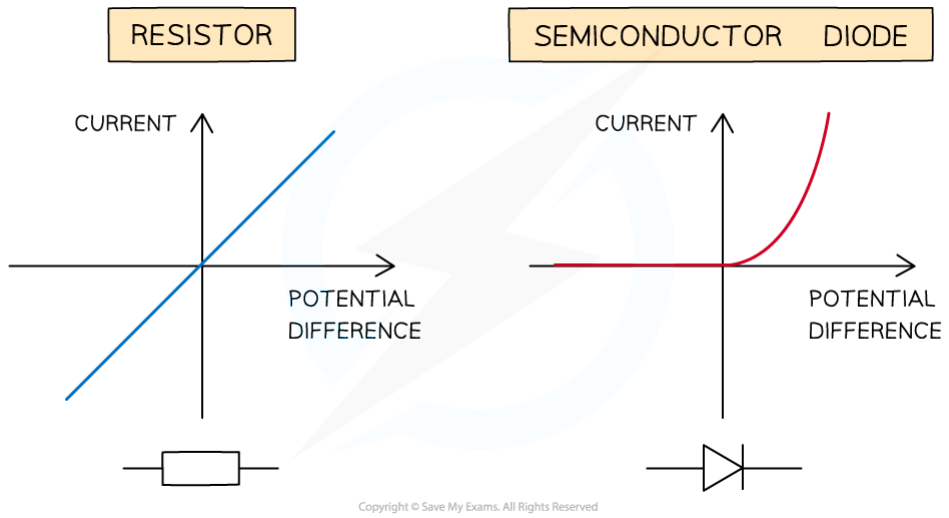
I-V Characteristics

- As the potential difference (voltage) across a component is increased, the current also increases (by Ohm's law)
- The precise relationship between voltage and current is different for different components and can be shown on an *I-V* graph:



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I-V characteristics for metallic conductor (e.g. resistor) and semiconductor diode

- The *I-V* graph for a metallic conductor at constant temperature e.g. a resistor, is very simple:
  - The current is **directly proportional** to the potential difference
  - This is demonstrated by the **straight line** graph through the origin
- The *I-V* graph for a semiconductor diode is slightly different. A diode is used in a circuit to allow current to flow only in a specific direction:
  - When the current is in the direction of the arrowhead symbol, this is **forward bias.** This is shown by the sharp increase in potential difference and current on the right side of the graph
  - When the diode is switched around, it does not conduct and is called **reverse bias.** This is shown by a zero reading of current or potential difference on the left side of the graph

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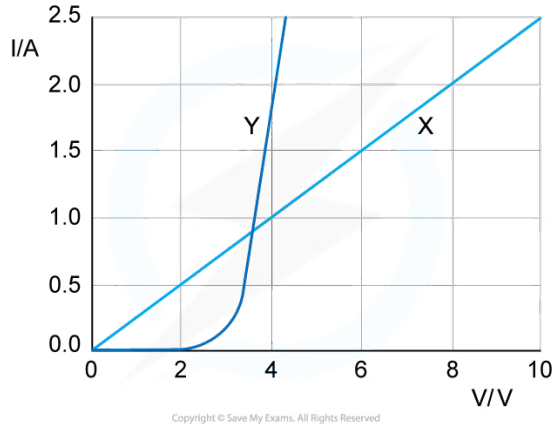
Worked Example

The *I–V* characteristic of two electrical component **X** and **Y** are shown.



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Which statement is correct?

A. The resistance of **X** increases as the current increases

B. At 2 V, the resistance of **X** is half the resistance of **Y**

C. **Y** is a semiconductor diode and **X** is a resistor

D. **X** is a resistor and **Y** is a filament lamp

Answer: **C**

- The *I–V* graph X is **linear**
  - This means the graph has a constant gradient. I/V and the resistance is therefore also constant (since gradient = 1/R)
  - This is the *I–V* graph for a conductor at constant temperature e.g. a resistor
- The *I–V* graph Y starts with zero gradient and then the gradient increases rapidly
  - This means it has infinite resistance at the start which then decreases rapidly
  - This is characters of a device that only has current in one direction e.g a semiconductor diode
- Therefore the answer is **C**

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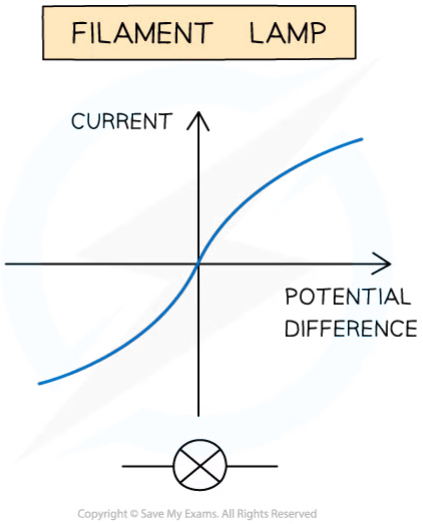
YOUR NOTES

Resistance in a Filament Lamp

- The *I–V* graph for a filament lamp shows the current increasing at a proportionally slower rate than the potential difference



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I–V characteristics for a filament lamp

- This is because:
  - As the current increases, the temperature of the filament in the lamp increases
  - Since the filament is a metal, the higher temperature causes an increase in resistance
  - Resistance opposes the current, causing the current to increase at a slower rate
- Where the graph is a straight line, the resistance is constant
- The resistance increases as the graph curves

Resistance and temperature

- All solids are made up of vibrating atoms
  - The higher the temperature, the faster these atoms vibrate
- Electric current is the flow of free electrons in a material
  - The electrons collide with the vibrating atoms which impedes their flow, hence the current **decreases**
- So, if the current decreases, then the resistance will increase (***V = IR***)
- Therefore, an increase in **temperature** causes an increase in **resistance**

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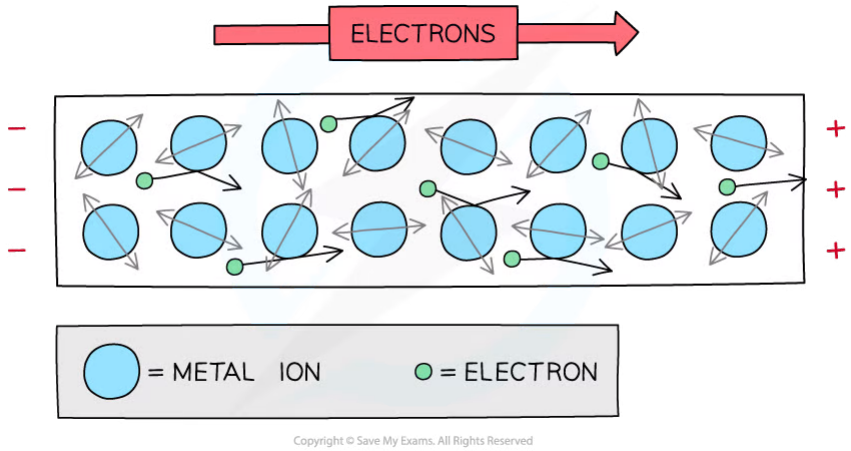
YOUR NOTES

9.3 Resistivity

9.3.1 Resistivity

Resistivity

- All materials have some **resistance** to the flow of charge
- As **free electrons move** through a metal wire, they collide with ions which get in their way
- As a result, they **transfer** some, or all, of their **kinetic energy** on **collision**, which causes electrical **heating**



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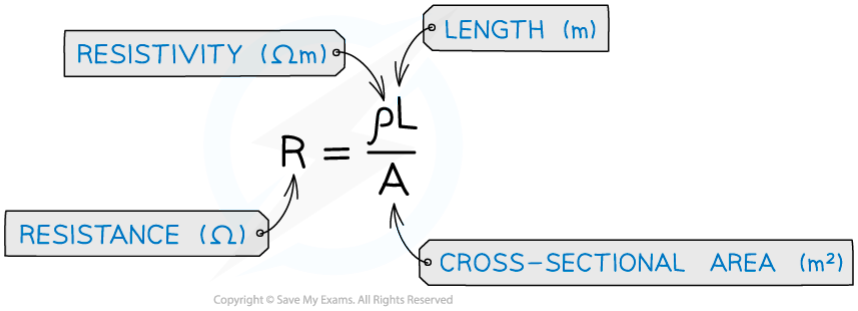
Free electrons collide with ions which resist their flow

- Since **current** is the **flow** of **charge**, the ions resisting their flow causes **resistance**
- Resistance depends on the **length** of the wire, the **cross-sectional area** through which the current is passing and the **resistivity** of the material



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Electrical resistance equation

- The resistivity equation shows that:
  - The **longer** the wire, the **greater** its resistance
  - The **thicker** the wire, the **smaller** its resistance

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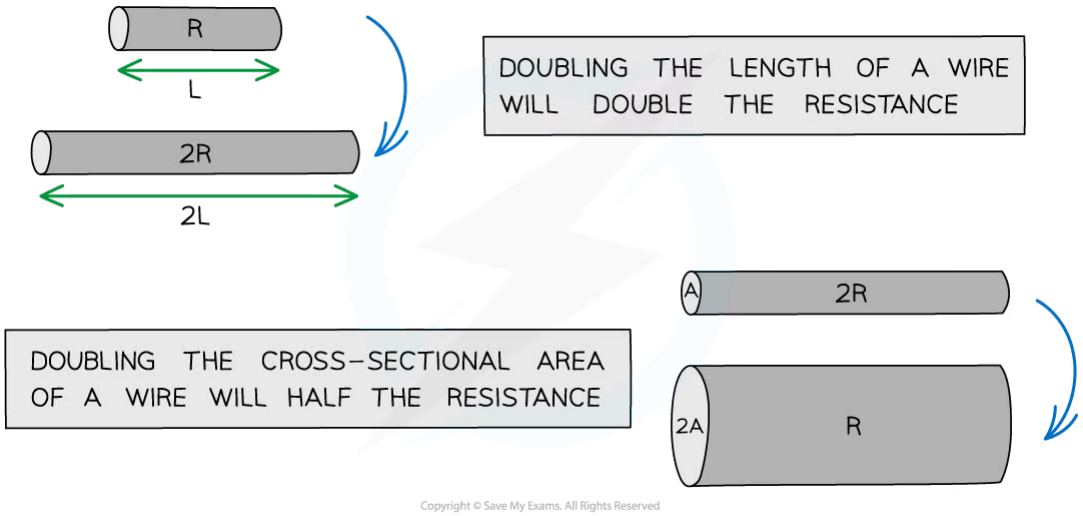

The length and width of the wire affect its resistance

- Resistivity is a property that describes the extent to which a material opposes the flow of electric current through it
- It is a property of the material, and is dependent on temperature
- Resistivity is measured in **Ω m**

Resistivity of some materials at room temperature

	Material	Resistivity ρ / Ωm
Metals	Copper	1.7×10^{-8}
	Gold	2.4×10^{-8}
	Aluminium	2.6×10^{-8}
Semiconductors	Germanium	0.6
	Silicon	2.3×10^{3}
Insulators	Glass	10^{12}
	Sulfur	10^{15}

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- The higher the resistivity of a material, the higher its resistance

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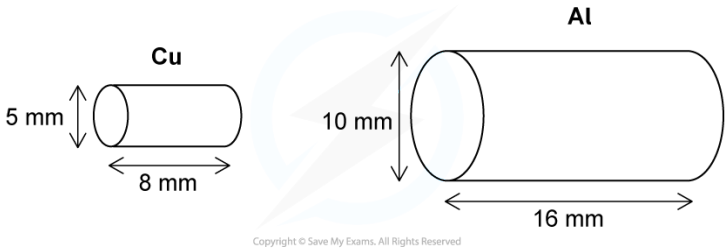
- This is why copper, with its relatively low resistivity at room temperature, is used for electrical wires — current flows through it very easily
- Insulators have such a high resistivity that virtually no current will flow through them

YOUR NOTES

Worked Example

Two electrically-conducting cylinders made from copper and aluminium respectively.

Their dimensions are shown below.



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Copper resistivity = 1.7×10^{-8} Ω m

Aluminium resistivity = 2.6×10^{-8} Ω mWhich cylinder is the better conductor?

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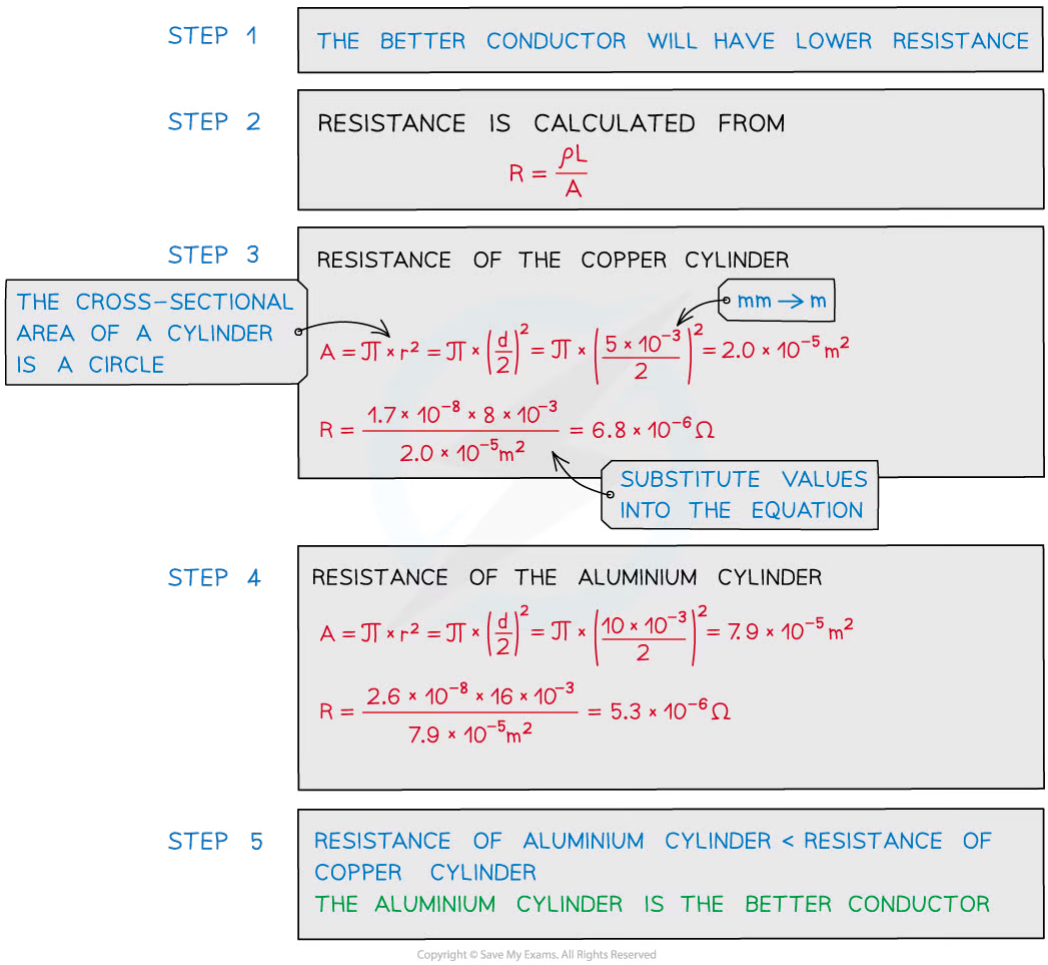
STEP 1
THE BETTER CONDUCTOR WILL HAVE LOWER RESISTANCE
STEP 2
RESISTANCE IS CALCULATED FROM
$R = \frac{\rho L}{A}$
STEP 3
THE CROSS-SECTIONAL AREA OF A CYLINDER IS A CIRCLE
RESISTANCE OF THE COPPER CYLINDER
mm → m
$A = \pi \times r^2 = \pi \times \left(\frac{d}{2}\right)^2 = \pi \times \left(\frac{5 \times 10^{-3}}{2}\right)^2 = 2.0 \times 10^{-5}\ m^2$
$R = \frac{1.7 \times 10^{-8} \times 8 \times 10^{-3}}{2.0 \times 10^{-5}\ m^2} = 6.8 \times 10^{-6}\ \Omega$
SUBSTITUTE VALUES INTO THE EQUATION
STEP 4
RESISTANCE OF THE ALUMINIUM CYLINDER
$A = \pi \times r^2 = \pi \times \left(\frac{d}{2}\right)^2 = \pi \times \left(\frac{10 \times 10^{-3}}{2}\right)^2 = 7.9 \times 10^{-5}\ m^2$
$R = \frac{2.6 \times 10^{-8} \times 16 \times 10^{-3}}{7.9 \times 10^{-5}\ m^2} = 5.3 \times 10^{-6}\ \Omega$
STEP 5
RESISTANCE OF ALUMINIUM CYLINDER < RESISTANCE OF COPPER CYLINDER
THE ALUMINIUM CYLINDER IS THE BETTER CONDUCTOR

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Exam Tip

- You won't need to memorise the value of the resistivity of any material, these will be given in the exam question.
- Remember if the cross-sectional area is a circle e.g. in a wire, it is proportional to the diameter squared. This means if the diameter doubles, the area quadruples causing the resistance to drop by a quarter.

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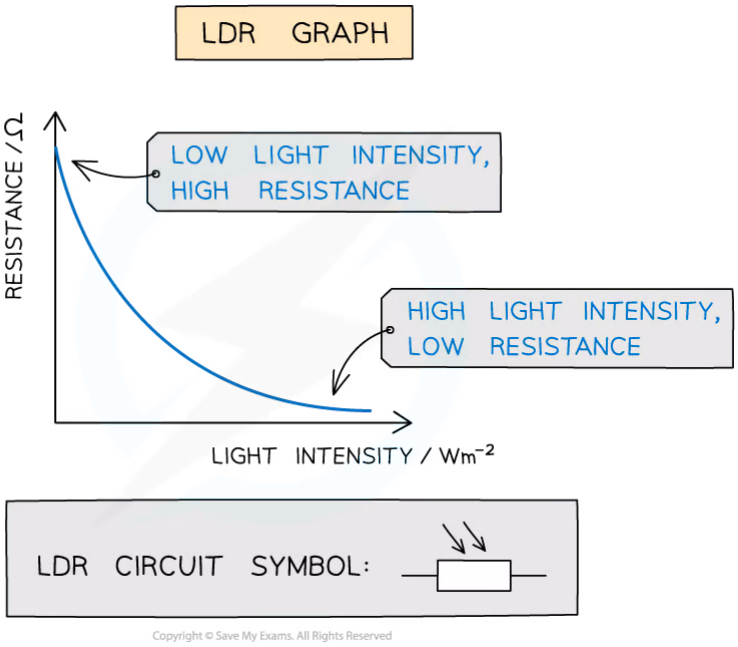
YOUR NOTES

Resistance in a Light-Dependent Resistor

- A light-dependent resistor (LDR) is a non-ohmic conductor and sensory resistor
- Its resistance automatically changes depending on the light energy falling onto it (illumination)
- As the **light intensity increases**, the **resistance** of an LDR **decreases**
- This is shown by the following graph:



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Graph of light intensity and resistance for an LDR

- LDRs can be used as light sensors, so, they are useful in circuits which automatically switch on lights when it gets dark, for example, street lighting and garden lights
  - In the dark, its resistance is very large (millions of ohms)
  - In bright light, its resistance is small (tens of ohms)

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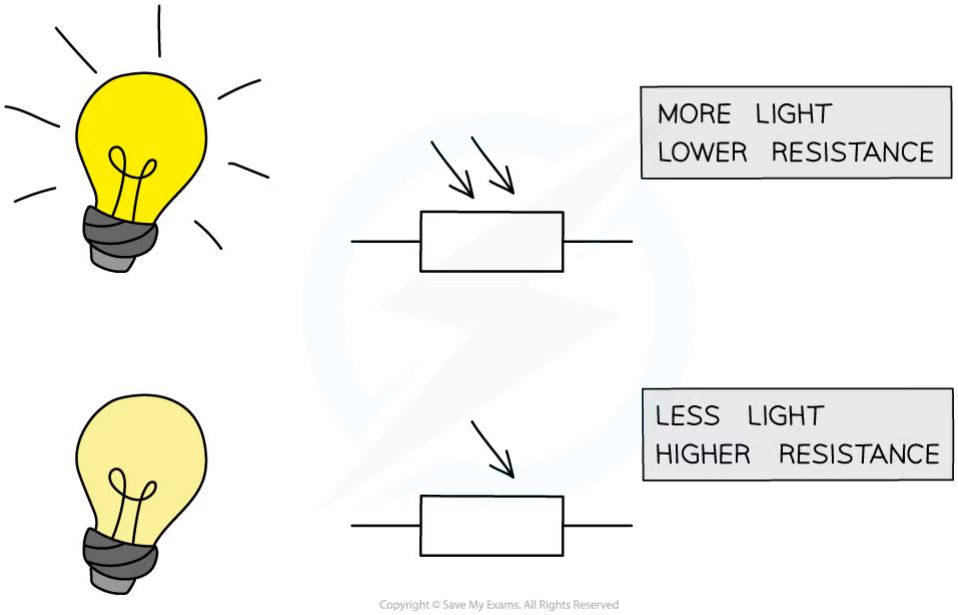

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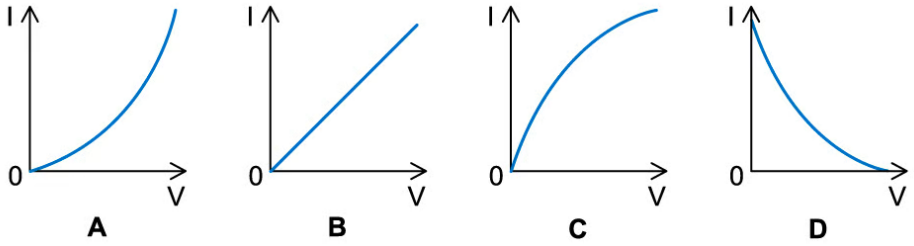
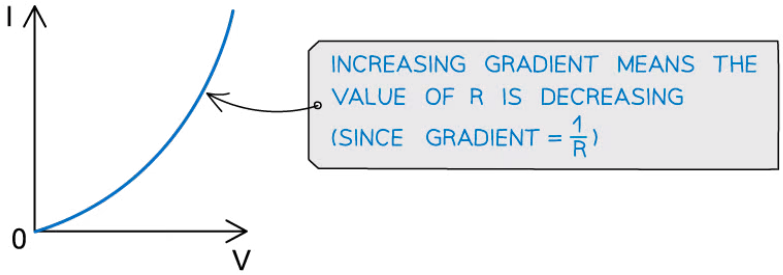
Resistance of an LDR depends on the light intensity falling on it

Worked Example

Which graph best represents the way in which the current I through an LDR depends upon the potential difference V across it?



ANSWER: A



- As the potential difference across the LDR increases, the light intensity increases causing its resistance to decrease
- Ohm's law states that ***V = IR***
- The resistance is equal to V/I or 1/R = I/V = gradient of the graph

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- Since *R* decreases, the value of 1/R increases, so the gradient must increase
- Therefore, *I* increases with the p.d with an increasing gradient

YOUR NOTES

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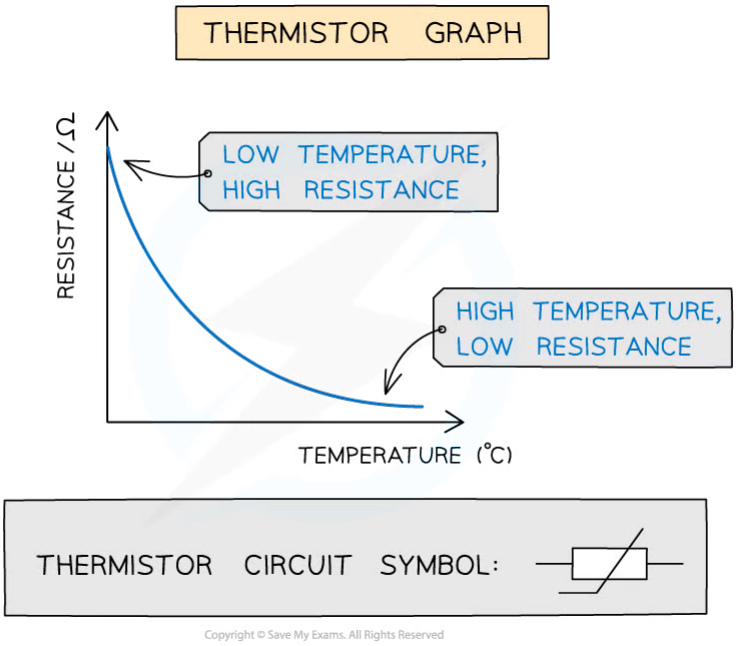
Resistance in a Thermistor

YOUR NOTES

- A thermistor is a non-ohmic conductor and sensory resistor
- Its resistance changes depending on its temperature
- As the temperature **increases** the resistance of a thermistor **decreases**
- This is shown by the following graph:



Graph of temperature and resistance for a thermistor

- Thermistors are temperature sensors and are used in circuits in ovens, fire alarms and digital thermometers
  - As the thermistor gets hotter, its resistance decreases
  - As the thermistor gets cooler, its resistance increases

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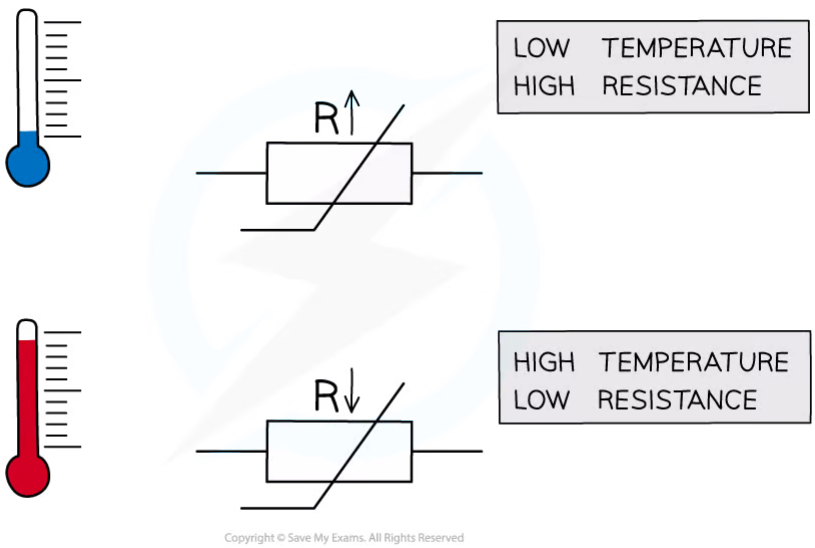

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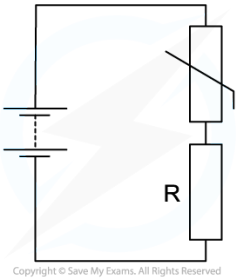
The resistance through a thermistor is dependent on the temperature of it

Worked Example

A thermistor is connected in series with a resistor *R* and a battery.



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The resistance of the thermistor is equal to the resistance of *R* at room temperature.When the temperature of the thermistor decreases, which statement is correct?

A. The p.d across the thermistor increases

B. The current in *R* increases

C. The current through the thermistor decreases

D. The p.d across *R* increases

ANSWER: A

- The resistance of the thermistor increases as the temperature decreases
- Since the thermistor and resistor *R* are connected in series, the current *I* in both of them is the same

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- Ohm's law states that $V = IR$
- Since the resistance of the thermistor increases, and I is the same, the potential difference V across it increases
- Therefore, statement **A** is correct

YOUR NOTES

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